

## Band structure in $^{12}\text{Be}$

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## BAND STRUCTURES IN $^{12}\text{Be}$ : EXPERIMENTAL RESULTS

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The structure of the neutron-rich isotope  $^{12}\text{Be}$  has been studied using different transfer reactions, which populate distinct structures in  $^{12}\text{Be}$ . This concerns two-neutron and three-neutron stripping reactions and two-proton pick-up reactions at incident energies of 15–20 MeV/u. Band structures of positive and negative parity are discussed.

### 1. Introduction

In neutron-rich Beryllium isotopes pronounced cluster structures can be found. These structures are strongly deformed and therefore rotational bands are built upon. In  $^{12}\text{Be}$  for example, a molecular band has been found by M. Freer *et al.*<sup>1</sup> using angular correlation measurements for the two  $^6\text{He}$  fragments or the  $^8\text{He} + ^4\text{He}$  fragments (Figs. 1(b), (c)) after inelastic excitation of the corresponding  $4^+$ ,  $6^+$ ,  $8^+$  band members (however, in a recent measurement at higher incident energy<sup>2</sup> some of the states were not confirmed). The  $0^+$  and  $2^+$  members of this band have been identified at 10.9 MeV and 11.3 MeV,<sup>3</sup> respectively, from the characteristic shapes of angular distributions for  $\ell = 0$  and  $\ell = 2$  angular-momentum transfers in inelastic  $\alpha$ -scattering on  $^{12}\text{Be}$ , in coincidence with the decay particles  $^6\text{He} + ^6\text{He}$ .

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|     | $^{12}\text{Be}$   | $S_x$     |
|-----|--|-----------|
| (a) | $^{10}\text{Be} \times 2n$   | 3.673 MeV |
| (b) | $^8\text{He} \times ^4\text{He}$                                     | 8.946 MeV |
| (c) | $^6\text{He} \times ^6\text{He}$                                     | 10.11 MeV |
| (d) | $\alpha \begin{smallmatrix} n & n \\ n & n \end{smallmatrix} \alpha$ | 12.06 MeV |

Fig. 1. Cluster configurations for  $^{12}\text{Be}$  (left) and corresponding particle thresholds  $S_x$  (right).

In the particle-stable region of excitation energies, below the 1n-threshold of  $^{12}\text{Be}$  at 3.168 MeV, four states were known: the  $0_1^+$  ground state, the  $2_1^+$  state at 2.10 MeV,<sup>4,5</sup> the  $0_2^+$  state at 2.24 MeV,<sup>6</sup> and the  $1_1^-$  state at 2.68 MeV.<sup>7</sup> From here up to the  $\alpha$ -particle threshold at 8.946 MeV only three states were known: the  $2_2^+$  state<sup>4,5</sup> at 4.56 MeV, the state at 5.70 MeV with  $(3^-, 4^+)$  assignments,<sup>4,5</sup> and an unassigned state at 8.6 MeV<sup>8</sup> observed in inelastic proton scattering in inverse kinematics.

## 2. Results from the Actual Transfer Reactions

We have used three different types of transfer reactions, each of which is populating primarily a distinct structure in  $^{12}\text{Be}$ , as will be shown in the following. These reactions are:

- (i) The two-proton pickup reaction on  $^{14}\text{C}$ :  
 $^{14}\text{C}(^{12}\text{C}, ^{14}\text{O})^{12}\text{Be}$ ,  $E_{\text{Lab}} = 231$  MeV,  $Q_0 = -30.06$  MeV,  $E_x = 0\text{--}20$  MeV
- (ii) The two-neutron stripping reaction on  $^{10}\text{Be}$ :  
 $^{10}\text{Be}(^{14}\text{N}, ^{12}\text{N})^{12}\text{Be}$ ,  $E_{\text{Lab}} = 216$  MeV,  $Q_0 = -26.94$  MeV,  $E_x = 0\text{--}20$  MeV
- (iii) The three-neutron stripping reactions on  $^9\text{Be}$ :
  - (a)  $^9\text{Be}(^{12}\text{C}, ^9\text{C})^{12}\text{Be}$ ,  $E_{\text{Lab}} = 231$  MeV,  $Q_0 = -42.64$  MeV,  $E_x = 0\text{--}18$  MeV
  - (b)  $^9\text{Be}(^{15}\text{N}, ^{12}\text{N})^{12}\text{Be}$ ,  $E_{\text{Lab}} = 240$  MeV,  $Q_0 = -30.97$  MeV,  $E_x = 5\text{--}26$  MeV

The measurements have been performed at the cyclotron and Q3D magnetic spectrometer of the Helmholtz-Zentrum Berlin (former name until May 2008: Hahn-Meitner-Institut Berlin).

### 2.1. The two-proton pickup reaction on $^{14}\text{C}$

The spectrum of the  $^{14}\text{C}(^{12}\text{C}, ^{14}\text{O})^{12}\text{Be}$  reaction (not shown here) is rather simple. Only five peaks are observed in the full range of measured excitation energies (for comparison: many more states are populated in the  $^{12}\text{C}(^{12}\text{C}, ^{14}\text{O})^{10}\text{Be}$  reaction<sup>9</sup>). Since the actual reaction produces proton-holes in the tightly bound  $^{14}\text{C}$  target

nucleus, the largest cross sections occur for the transitions to the ground state and the  $2_1^+$  state, but also the  $2_2^+$  state at 4.56 MeV is well populated. The latter is considered to be a member of the  $0_2^+$ -band, which is located at 2.24 MeV. The corresponding band head could not be resolved from the strong  $2_1^+$  state at 2.10 MeV, but it has a sizable overlap with the high-energy tail of the 2.10 MeV peak and may be hidden there. Two broad resonances are observed at higher excitation energies, at 9.6 MeV and 18.95 MeV. As a preliminary result, these are considered to form a rotational band together with the  $0_2^+$  and  $2_2^+$  states.

## 2.2. The two-neutron stripping reaction on $^{10}\text{Be}$

Figure 2 shows the full spectrum of the  $^{10}\text{Be}(^{14}\text{N}, ^{12}\text{N})^{12}\text{Be}$  reaction. Since the target material was Beryllium-oxide ( $\text{BeO}$ ), large contributions from  $^{16}\text{O}$  are observed, but also some contributions from  $^{12}\text{C}$  (the strongest  $^{14}\text{C}$ -line at 10.74 MeV is indicated in Fig. 2). Spectra on  $^{12}\text{C}$  and  $^{16}\text{O}$  ( $\text{V}_2\text{O}_5$ -material) have been measured separately and their normalizations were fitted simultaneously with the peaks of  $^{12}\text{Be}$ . As a result from this analysis it turned out that this reaction also populates only a few states of  $^{12}\text{Be}$ , namely the states at 0.00 MeV, 2.10 MeV, 4.56 MeV, 5.70 MeV, 6.25(5) MeV (the latter state was localized only recently in a reanalysis of the spectrum) and 11.2 MeV. In the excitation energy range from 7–20 MeV only one single peak is observed! Obviously the structure of excited states in this range does not fit to a  $^{10}\text{Be}_{g.s.}$  core. We will see in the next section, that a  $^9\text{Be}_{g.s.}$  core opens the window for the population of many states in this excitation energy region.

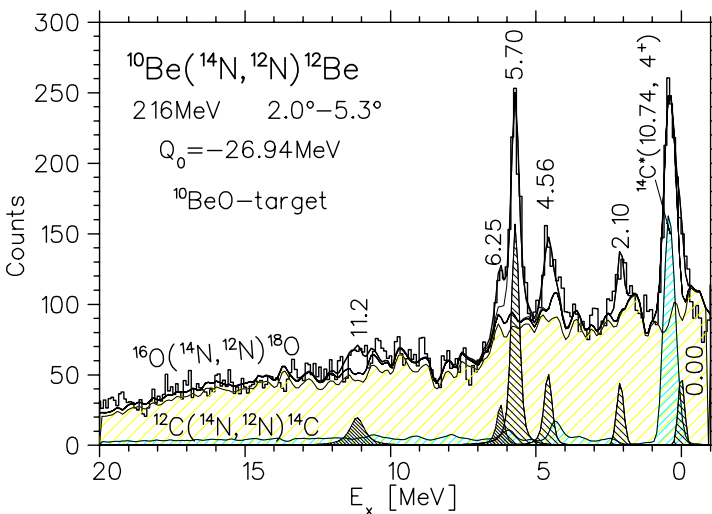


Fig. 2. Spectrum of the two-neutron transfer reaction ( $^{14}\text{N}, ^{12}\text{N}$ ) on a  $^{10}\text{BeO}$  target at 216 MeV. The sum of background contributions resulting from the  $^{16}\text{O}$  and  $^{12}\text{C}$  content of the target is indicated by the hatched area with wide spacing, the part from  $^{16}\text{O}$  (yellow) is dominant.

### 2.3. The three-neutron stripping reactions on $^9\text{Be}$

The  $^9\text{Be}(^{12}\text{C}, ^9\text{C})^{12}\text{Be}$  reaction has a very large negative Q-value, therefore the cross sections are very small. But the resolution is rather good, and narrow states can be well identified even on the background resulting from the  $^{16}\text{O}$  in the target (see Fig. 3). The new state just above the 5.70 MeV peak is again observed, here at 6.30(5) MeV. In this reaction nine states can be localized at 7–17 MeV excitation energy in contrast to the two-neutron stripping reaction on  $^{10}\text{Be}$ . Such a large number of states is also observed in the  $^9\text{Be}(^{15}\text{N}, ^{12}\text{N})^{12}\text{Be}$  reaction (not shown here). The states marked in red in Fig. 3 (upward hatched area) are tentatively assigned as members of a  $K=1^-$  band. Details of the analysis will be given in an extended publication.

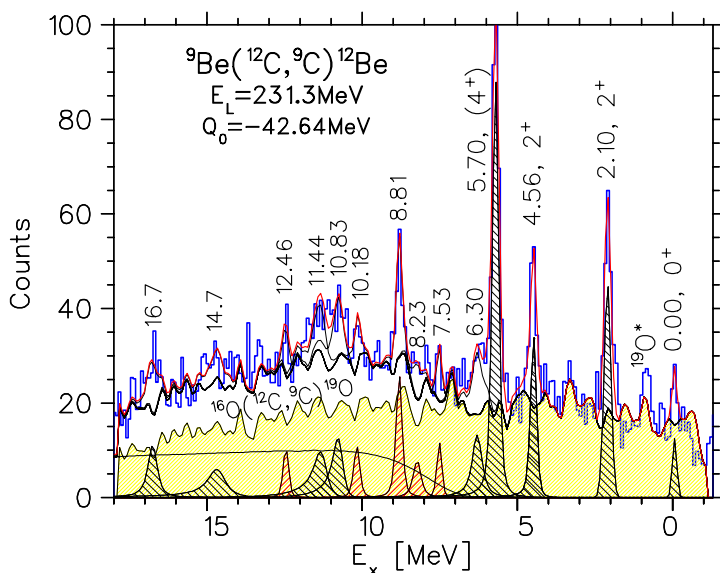


Fig. 3. Spectrum of the  $^9\text{Be}(^{12}\text{C}, ^9\text{C})^{12}\text{Be}$  three-neutron transfer reaction at 231 MeV. The background from the  $^{16}\text{O}$  target contamination is indicated by the yellow hatched area.

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